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The Blast Power of the Hiroshima and Nagasaki Atomic Bombs

W. G. Penney

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The Blast Power of the Hiroshima and Nagasaki Atomic Bombs

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The Manhattan District group of scientists that was sent to the Mariana Islands in the Pacific to assemble the atomic bombs for use against Japan took the opportunity, as soon as occupation of Japan began, to send a small team into Hiroshima and Nagasaki with the object of observing the damage caused by the two atomic bombs actually used. No clear programme was possible before the cities had been seen. The team walked about, more or less at random, until some significant feature was noticed. Notes were made and gradually the search became organised and directed. The Report now presented represents deductions from notes made by the writer in the two cities and from samples brought back to England for study. Notes were made and samples were brought back only where the conditions of failure of a specimen seemed critical or significant. For example, if something had failed in the blast, the observation was only recorded if several other similar objects in the same group had not failed, or if the degree of failure appeared susceptible to inclusion in a mathematical treatment. To test the validity of some of the conclusions, experiments were made at Bikini, and the present Report takes into account these observations. As a result of this work, the author now has considerable confidence that the Hiroshima bomb was equivalent in blast producing power to a single spherical bare charge of TNT weighing 7000 tons, while the Nagasaki bomb was similarly equivalent to 17,000 tons. In both cases, and throughout this Report, a ton is taken to be 2240 lb., rather than the U.S. (or short) ton of 2000 lb.

The present Report is substantially a summary of the Secret parts of a report given to General Groves on January 2nd, 1946; large sections of the report not covered here were reproduced in the Manhattan District Reports (The Atomic Bombings of Hiroshima and Nagasaki). The original report was required quickly and although it was produced to time, the author was never satisfied with the accuracy of some of the model-scale work. Improved experimental methods have now been introduced and the opportunity has also been taken of introducing two or three small corrections. The data now presented are considered to be interpreted as accurately as possible, whereas this was not true of all the results given in the original report.

The Hiroshima bomb used U 235 as the explosive agent. No field trial was made to test the functioning or the blast performance of the complete weapon, and the burst over Hiroshima may well be the only example where such a bomb will ever be detonated. From the military point of view it is therefore extremely important that the power of the bomb should be assessed as accurately as possible. It is considered that the results quoted here for Hiroshima are in fact little inferior in accuracy to those which could be obtained from a field trial. The results given here for Nagasaki are not as comprehensive as those for Hiroshima.

The Nagasaki bomb was identical with that tested in New Mexico before the atomic bombing of Japan. Two further bombs of the same construction were tried at Bikini. The three sets of results on the New Mexico bomb and the two Bikini bombs all agreed within a few per cent. that the blast equivalent was 17,000 tons, thus offering strong presumptive evidence that the Nagasaki bomb was also 17,000. This expectation is strongly confirmed by three observations at Nagasaki in which considerable confidence may be placed.

Three main methods were discovered for estimating the strength of the blast wave. The first two give a value for the peak hydrostatic pressure, while the third gives a value for the maximum air speed, and thence, from the shock wave equations, the peak hydrostatic pressure.

Compression of Cans and Drums.

One of the simplest and most effective methods of estimating the peak pressure was from the crushing of petrol cans, oil drums or any other thin metal vessel with a small opening. The blast pressure comes on to the can so quickly that the walls collapse inwards before any appreciable amount of air has time to rush in through the opening. The air inside is compressed adiabatically to such a degree that the pressure inside is less by a certain amount than the pressure outside, this amount being the pressure difference that the walls can stand in their crumpled state. As the pressure outside falls, due to the decay of the blast, the air inside escapes without re-inflating the can. It may be shown without difficulty that the assumptions of practically instantaneous collapse (i.e. no air rushing in, and no decay of the primary blast wave), and no re-inflating are valid for the specimens actually obtained.

As the peak hydrostatic pressure in the blast rises above about 10 p.s.i., the pressures at the front and back of the can are not quite the same; the drag pressure at 10 p.s.i. is about 1 p.s.i. To this extent, it is not quite clear which pressure the can actually records. However, in most cases, the cans actually found were in sheltered positions, and were not thought to record extra effects due to windage.

Let Vo be the initial volume of the can, and Vc its crushed volume. Then the pressure rise inside the can was

$$p_o \left[(Vo/Vc)^{\alpha} - 1 \right]$$

where p_o is atmospheric pressure, and α is the ratio of the two specific heats of air ($\alpha = 1.4$).

The peak hydrostatic pressure in the blast was taken to be

$$P = P_c + p_o \left[(Vo/Vc)^{1.4} - 1 \right] \qquad (1)$$

where P_c is the strength of the can against external pressure when the can is in its crushed state. Experiments were made on most specimens to measure P_c. In other cases, P_c was measured for cans of identical construction.

The blast wave from the air-burst Bikini bomb was measured by means of the compression of 5-gallon and 55-gallon (U.S. gallons) petrol cans and drums. The results were surprisingly successful and reproduced within 2 per cent. the pressure-distance curves obtained from more 'scientific' devices. Indeed, the results from the cans showed less scatter than the other instruments since the latter usually required to be set up either exactly facing the blast, or in the side-on position. As the bomb was to be dropped from an aircraft, it was impossible to set out the instruments with the alignment that they needed to give accurate readings, and the results actually obtained, due partly to the large bombing error and to the movement of the ships on their moorings, showed considerable scatter. However, so many readings were taken that firm conclusions about the blast were obtained.

Some general remarks about the accuracy of the results that can be obtained from the compression of cans may be of general interest.

Flimsy cans, with a strength 2-3 p.s.i. before collapse, are quite accurate in the maximum pressure range 3-15 p.s.i. Accuracy of the order 10 per cent. is feasible for long duration blast, such as that from atomic bombs. At higher pressures, windage corrections introduce uncertainties, and the method is practically useless at pressures above 20-25 p.s.i. Strong walled cans, such as 50-gallon drums, are constant in their collapsing pressure, but the strength in the collapsed state is very variable. Thus, the uncertainty in P calculated from (1) is unacceptably large, and the deductions of peak pressure are therefore unreliable. Windage corrections are also large but unprecise.

Dishing of Panels

A number of examples were found where panels had been 'dished' by the hydrostatic pressure of the blast. One side of the panel was immune to the blast, while the other side experienced the full hydrostatic pressure. Model experiments were made to estimate the pressure that caused failure.

The most satisfactory examples of this class were concrete panels forming the ground floor of a building; underneath the floor was a basement which had been bricked up to form an air raid shelter. Other examples were dished tops of steel cabinets, a dished safe door and a partially broken wooden floor.

Drag Problems.

An interesting series of observations was made on the bending of steel flag-poles and lightning conductors in the wind from the explosion. Similar examples were the bending of steel ladders, the snapping of telegraph or power-line poles, and the overturning of memorial ancestral stones.

The drag on an object of area A in an air stream of density ρ and mass velocity u is by definition FA, where

$$F = \frac{1}{2} C_D \rho u^2, \qquad (2)$$

and C_D is the drag coefficient. For a pipe of diameter D and length L in a transverse wind

$$A = DL$$

The drag coefficient is a function of Reynolds number R and Mach number M, as well as the roughness of the pipe

$$R = Du\rho/\mu, \qquad M = u/c$$

where μ is the coefficient of viscosity and c is the velocity of sound.

The flagpoles were all about 2.5" diameter and were fairly smooth. The Reynolds number was nearly 10^6, and the Mach number was about 0.5. From the literature, the drag coefficient was between 0.4 and 0.6 and the experimental curve was used to obtain the value appropriate to the circumstances. One can show that if there is a 10 per cent. uncertainty in the drag coefficient, then the peak shock overpressure calculated from (2) is only uncertain to 4 per cent. if the shock overpressure is about 10 p.s.i., and is only 5 per cent. uncertain if the shock overpressure is 15 p.s.i. As the peak overpressures deduced from the examples noted in the two cities were in this range, the uncertainty in the deduced peak pressure due to uncertainty in the drag coefficient was only a few per cent.

The measurement actually made was the angle of yield of a steel pipe which had just failed in the wind. Only those cases were noted where the angle of yield was small, usually 3-5°. The dimensions of the pipe were measured, and is some cases a sample length of the pipe was brought back in order to determine the yielding bending moment M. Then from equation (2)

$$M = \frac{1}{2} FAL^2$$

This equation gave F, and using (2), as well as the Rankine-Hugoniot shock wave equations, the maximum overpressure in the blast could be estimated. A correction was then added to allow for the fact that the blast wave was not a continuous steady wind, but decayed fairly quickly from its peak value. The correction was usually 5-20 per cent. The actual details are elaborate and in any case are not exact, and will not be given here. However, it is thought that in certain favourable examples, the accuracy of the final result is good, and the error could hardly exceed 10 per cent.

To substantiate the claim that the accuracy was of the order 10 per cent., pipes of the same type were put on a number of ships at Bikini, and near to them other more conventional instruments were placed. Photograph 2 shows one example. The analysis summarised above was applied and the results in this case compared with the peak pressure obtained from the rupturing of a number of aluminium foils contained in the "foil meter tower". The results were completely satisfactory.

RESULTS

Compression of Cans.

Four blue-print containers of excellent construction, one of which is shown in photograph 7, were found in the Communications Bureau, 5000 ft. ENE of the point under the explosion ground zero at Hiroshima. The lids, which had rubber washers, were tightened into position with a lever on a handle. The containers, even in their crushed condition, were almost air tight; as the pressure outside fell, the lid opened, leaving the can in an exact register of the maximum pressure. All four were equally crushed and one was brought back for test.

Original volume	57125 c.c
Volume in collapsed state	51525 c.c
Loss in volume	9.8 per cent.
Pressure developed	2.28 p.s.i.
Strength in the collapsed state	0.81 p.s.i.
Maximum pressure	3.1 p.s.i.

The volume of the floor of the building in which it was found, divided by the window area, was 30 feet. We now apply a correction to allow for the fact that the maximum pressure inside is not quite the hydrostatic pressure outside.

If the hydrostatic pressure outside decays according to the law $Pe^{-t/T}$, and τ is the time L/c, where L is the volume of the floor divided by the window area and c is the velocity of sound, then the maximum pressure reached inside is

$$Pn^{-1/n}$$

where n is T/τ.

As a result of all our observations, we decided that the blast in Hiroshima was equal to that of 7000 tons. Hence T = 0.3 secs. and τ = 0.025 secs..

The peak hydrostatic pressure at 5000 feet is therefore deduced as $3.1\,(12)^{1/12}$ or 3.8 p.s.i.

P = 3.8 p.s.i. at R = 5000 ft. in Hiroshima.

A crushed can was found 4100 ft. S. of ground zero in the yard of a small machine shop in Hiroshima. The compression ratio was 1.22, and the adiabatic pressure was 4.65 p.s.i. The strength of the can in the crushed state was about 1.3 p.s.i. Hence

P = 6 p.s.i. at R = 4100 ft. in Hiroshima.

A crushed 40-gallon petrol can was found in the open, 900 ft. from the ground zero in the yard of the Prefectural Display Hall on the away side of the blast in Hiroshima. From tests made on this particular type of can, collapse occurs at 18-20 p.s.i. Experiment has shown however, that equation (1) is not reliable at such high pressures, although collapse does not occur below 18 p.s.i. The collapsed cans can withstand 15-25 p.s.i. The compression ratio was about 1.5, so that the maximum pressure was of the order 20 p.s.i., and might have been 25 p.s.i. Some deduction might be necessary to allow for wind pressure. We have with reasonable certainty that the maximum pressure was 20-25 p.s.i. at R = 900 ft.

A large number of petrol cans 9"x 9"x 13.5" were found in Nagasaki. Many of them were in the Mitsubishi steel works. Some had obviously had petrol, oil or water in them at the time of the explosion. Two or three which appeared to be empty at the time of the explosion were found in the forging shop 3200 ft. S of ground zero. All the cans were about equally crushed, and one on which measurements were made showed a loss of volume of 35 per cent. The adiabatic pressure reached was 13 p.s.i., and adding 1 p.s.i. for the strength of the can, we get

P = 14 p.s.i. at R = 3200 ft. in Nagasaki

No correction is considered necessary for windage or for the build-up of pressure in the shop. The light corrugated iron roof and the heavy furnaces and winches were considered enough to give protection from the wind but not to delay the full application of the hydrostatic pressure.

Cans of this type were found slightly collapsed at 8500 ft. in Nagasaki, but the writer was unable to find any collapsed beyond 4500 feet in Hiroshima. These cans collapse at about 2.5 p.s.i. and if the Nagasaki bomb was 17,000 tons, it should have been possible to find collapsed specimens out to a radius of 10,000 ft.; similarly, if the Hiroshima bomb was 7000 tons, collapsed specimens should have been found out to 8400 ft.

<u>Drag Problems</u>

Telegraph poles and chimney stacks on the whole gave disappointing results. Chimney stacks only collapsed near ground zero, where the blast was not transverse to the chimney. It was therefore necessary to allow for both the incident and reflected shocks and the calculations proved to be too complicated. Telegraph poles underneath the explosions were usually still standing, but further away, they were usually snapped off while the rest were uprooted.

In Nagasaki all the poles, except at the centre, were down, out to a radius 3500 ft., whilst most were standing at 4500 ft. As a rule, the poles carried so many cross pieces and wires that calculations were impossible. One pole, of excellent wood, carried only a few wires running in the direction of the blast. The cross piece was small, and from tests made on a sample of the wood, it was estimated that the peak pressure must have been about 15 p.s.i. at 3400 ft. However, no confidence is expressed in this result, although it agrees well with the value read off the blast curve.

Two observations on the bending of steel tubular flagpoles in Hiroshima, now to be described, are regarded as giving estimates of high accuracy. The first flagpole, from the roof of the bank building 3200 ft. E. of ground zero, was of length 289", outside diameter 2.40", thickness 0.140", had yielded at the bottom through an angle 0.114 radians. The yielding bending moment was measured experimentally to be 9.2×10^4 poundals ft. The drag coefficient finally selected was 0.52, and the peak shock overpressure, after corrections for the yielding had been applied (the correction was 2.2 p.s.i.) was 9.2 p.s.i. Hence

P = 9.2 p.s.i. at R = 3200 ft. in Hiroshima.

The second flagpole, identical in material with the first, was on the Electric Company Building 2100 ft. from ground zero. The length was 114" and the pole had yielded at the bottom through an angle 0.075 radians. The drag coefficient finally selected was 0.65, and the peak shock overpressure was deduced to be 15.4 p.s.i. The correction on pressure for yield was in this case only 1.8 p.s.i. Hence

P = 15.4 p.s.i. at R = 2100 ft. in Hiroshima.

Some half a dozen other examples of the same type were found in Hiroshima, but the objects were not simple cylinders, and the results, although entirely concordant with our final blast curve, were not considered as reliable as those given above.

Unfortunately, no examples of slightly bent flagpoles were found in Nagasaki. The only two substantial buildings near ground zero were the Shiroyama School and the Medical School. One school had a lightning conductor of substantial construction, but this was bent over horizontally, was flattened and the top pulled out. No deductions could be drawn.

Estimates were made both for Hiroshima and Nagasaki from the overturning of memorial stones. These stones were of rectangular cross section, made of artificial granite (density 2.38 g./cc.), and were simply resting in a shallow cavity (0.05" deep) of the same shape in a larger tablet. The wind blew some of them over, and the observations consisted of measuring the dimensions of the overturned stones with the greatest height to depth ratio. Notes were only taken when the stones faced the blast. The drag coefficient was taken to be 0.8 in the region P = 8 p.s.i., and corrections (usually of the order 25 to 50%) had to be applied to the peak pressure to allow for the decay of the blast.

As examples of this method it was found that

P = 7.0 at R = 3800 ft. in Hiroshima

P = 8.5 at R = 4700 ft. in Nagasaki

Panel Problems

A fairly good estimate of the peak pressure 600 ft. from ground zero in Hiroshima was obtained from the cracking and breakage of some glass panels in a mail chute (American type). This chute went from the top floor to the ground floor in the large bank building SE of ground zero, on the SW corner of the T junction of the street car lines. There were three panels on each floor, all below the posting orifice. The panels were 2'6", 1'0" and 1'0" respectively in this order descending. The distance between the supporting steel edges on either side was 6.0". The support against fracture was simple. Four of the six panels on the ground and first floors were fractured, and one of the two which escaped was a 2'6" panel. All but one of the panels on the higher floors were intact. It appears that the maximum pressure near the ground was greater than it was higher up. Since this could be so only to a small degree, we assume that the pressure near the ground was only just enough to burst the panels.

Specimens of the glass showed that the tensile strength against bending fracture was 9000 lb./in^2. We therefore are able to estimate that the peak pressure inside the building was 25 p.s.i. Correcting for the time to build up to this pressure, and the decay of pressure outside the building, we get that the maximum pressure in the blast was 30 p.s.i. Hence

$$P = 30 \text{ p.s.i. at } R = 600 \text{ ft. in Hiroshima}$$

The telephone exchange in Hiroshima 3800 ft. WNW of ground zero had a small wooden floor as a superstructure on the main ground floor, which was of concrete. The wooden floor was covered by sleeping mats at the time of the explosion, and the pressure of the blast was enough to break the joists of one of the two weakest panels, namely the end ones. One of the seven joists of the panel that failed had been removed, and presumably just reduced the strength enough to cause failure. After a number of tests on specimens brought back, and some rather elaborate beam calculations, it was deduced that the maximum pressure reached in the building was 6.6 p.s.i., and this was increased to 7.5 p.s.i. as the value for the peak shock overpressure

$$P = 7.5 \text{ p.s.i. at } R = 3800 \text{ in Hiroshima}$$

The uncertainty in this estimate was of the order 1 p.s.i., and was largely due to the difficulty of allowing for the natural period of vibration of the floor (calculated as 10 milliseconds).

Two panel problems are now described, one from Nagasaki and one from Hiroshima, where the results obtained are considered to be quite accurate.

The metal top of a tool chest 16" x 18" in the machine shop 2200 ft. N of ground zero in Nagasaki was dished $\frac{3}{4}$" at the centre. The thickness of the metal was 0.056". The rest of the tool chest was undamaged; the side walls and front were of much stouter construction and were heavily braced. A model experiment was made, and the hydrostatic pressure to cause this yield was found to be 22 p.s.i. The pressure was put on the model from a rubber bag, mounted in a box, with an opening where the model was placed. By pumping up the bag and measuring the pressure, the load-displacement curve was obtained. To allow for the protection given by the building, the peak pressure was increased by 12%. Thus the peak shock pressure at 2200 ft. was estimated to be 25 p.s.i.

A safe of old and cheap design was found in a bank building 200 ft. from ground zero in Hiroshima. The two mild steel doors, 72.4" x 24.7" x 0.363" were dished, and the set at the meeting edge, where they still overlapped closely, was 4". A model was made, and a hydrostatic load was applied by means of the inflation of the rubber bag described above. The peak pressure in the shock was thus estimated to be 35 p.s.i.

A description is now given of a pair of important observations. The importance lies in the fact that the two cases were as nearly identical as one could hope, and one was in Hiroshima while the other was in Nagasaki.

The ground floor of the Administration building of the Torpedo Works in Nagasaki, 4050 ft. N of ground zero, acted as the roof of an air raid shelter. The shelter was practically unventilated; the windows, which were in any case small, had been almost entirely bricked-up. The only opening was the door at the top of the stairs connecting the ground floor to the basement. The basement was about 100' x 30' x 9'. Thus, when the explosion wave reached the building, the pressure in the shelter did not change. On the other hand, the large window space at ground floor level allowed the pressure inside to rise very rapidly. The effect of the pressure difference on the two sides of the reinforced concrete floor was to dish in most of the panels. A careful study was made of the construction of the floor by knocking a 4' x 4' hole in it, and details of the reinforcements were obtained. There were three similar panels and the dishing was 9.5", 9.8" and 4".

Practically the same situation to that described was also found in the Radio Building in Hiroshima 3100 ft. N.E. of ground zero. The reinforcements were practically the same; the thickness of the concrete was practically the same; and the dishing was practically the same. Here there were two identical panels; one was dished 10" and the other was intact.

The problem as to what the pressure was to cause these observed dishings was put in 1945 to the Concrete Section of the Road Research Laboratory. The concrete was considered to be of reasonable quality, the Radio Building sample perhaps being slightly the better, as might be expected, since the Radio Building was built before the war, while the other was built during the war. The exact amount of dish was not considered significant since the panels would give their maximum resistance before they first failed.

The panels at Nagasaki were 15' x 23', while those at Hiroshima were 14'3" x 20'. There was 25% more steel in the Nagasaki panel per square foot than in Hiroshima, but the depth between centres was the same.

Absolute estimates of the collapsing pressures could not be given by the Road Research Laboratory, but it was thought that the figure must be between 10 and 20 p.s.i., probably much nearer to the former figure. By drawing a smooth curve through the other results obtained at Hiroshima, the pressure was 9 p.s.i., and it was considered that 10 p.s.i. was therefore an accurate value for Nagasaki. This value of 10 p.s.i. at 4050 ft. in fact agrees very closely with the 17,000 ton value (9.5 p.s.i.) and thus produces results entirely concordant with our expectations.

We thus have

$$\left.\begin{array}{l} P = 9 \text{ p.s.i. at } R = 3100 \text{ ft. in Hiroshima} \\ P = 10 \text{ p.s.i. at } R = 4050 \text{ ft. in Nagasaki} \end{array}\right)$$

To be strictly logical, we should regard only one of these two observations to be independent.

Summary of the Results on Peak Pressure

We now collect, in tabular form, the results previously described.

Hiroshima

Distance from Ground zero (feet)	Maximum Blast Overpressure (p.s.i.)	Method of Determination
200	35	Dished door of safe
600	30-35	Breaking of glass panel
900	20-25	Collapse of oil drum
2100	15.4	Bending of flag pole
3100	9.0	Failure of concrete panel
3200	9.2	Bending of flag pole
3800	7.0	Overturning of memorial stones
3800	7.5	Failure of wooden floor
4100	6	Crushed can
5000	3.8	Crushing of blue print can

Nagasaki

2000	25	Dished metal top of cabinet
3200	14	Collapse of petrol can
3400	~ 15	Snapped telegraph pole
4050	10	Failure of concrete panel
4700	8.5	Overturning of memorial stones

Figure 1 shows the observations at Hiroshima plotted as a function of distance. The smooth curve through the results is that for the explosion of a 7200 ton bare T.N.T. charge, 1800 feet above ground level. This curve has been constructed by scaling distances up by a factor of 60 from the experimental measurements of 67 lb. bare T.N.T/R.D.X. charges exploded 30 ft. above ground. The results are given in A.R.D. Explosives Report 16/45.

Figure 1 also shows the observations at Nagasaki, plotted as a function of distance, and the smooth curve drawn through the points is that for 17,000 tons of T.N.T. exploded 1800 ft. above the ground. This curve, also, was obtained from A.R.D. Report 16/45, scaled up by a factor 80 from 67 lb. bare R.D.X./T.N.T. charges exploded 22 ft. above ground level.

As a matter of interest, it is noted that if the Hiroshima bomb was actually equivalent to 7200 tons of T.N.T., the over-pressure on the ground immediately underneath was 36 p.s.i. Similarly, if the Nagasaki bomb were 17,000 tons, the over-pressure on the ground immediately underneath was 100 p.s.i.

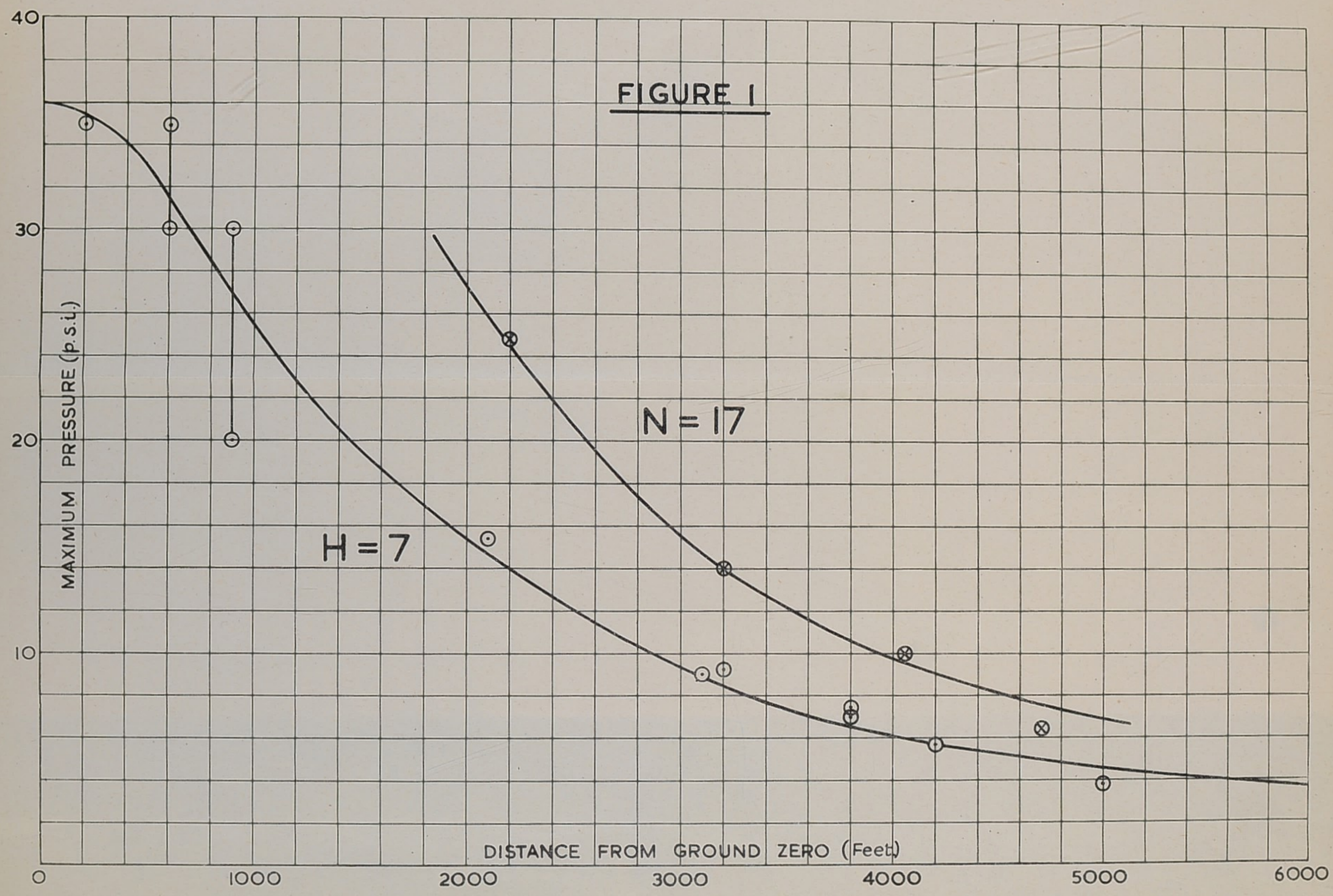
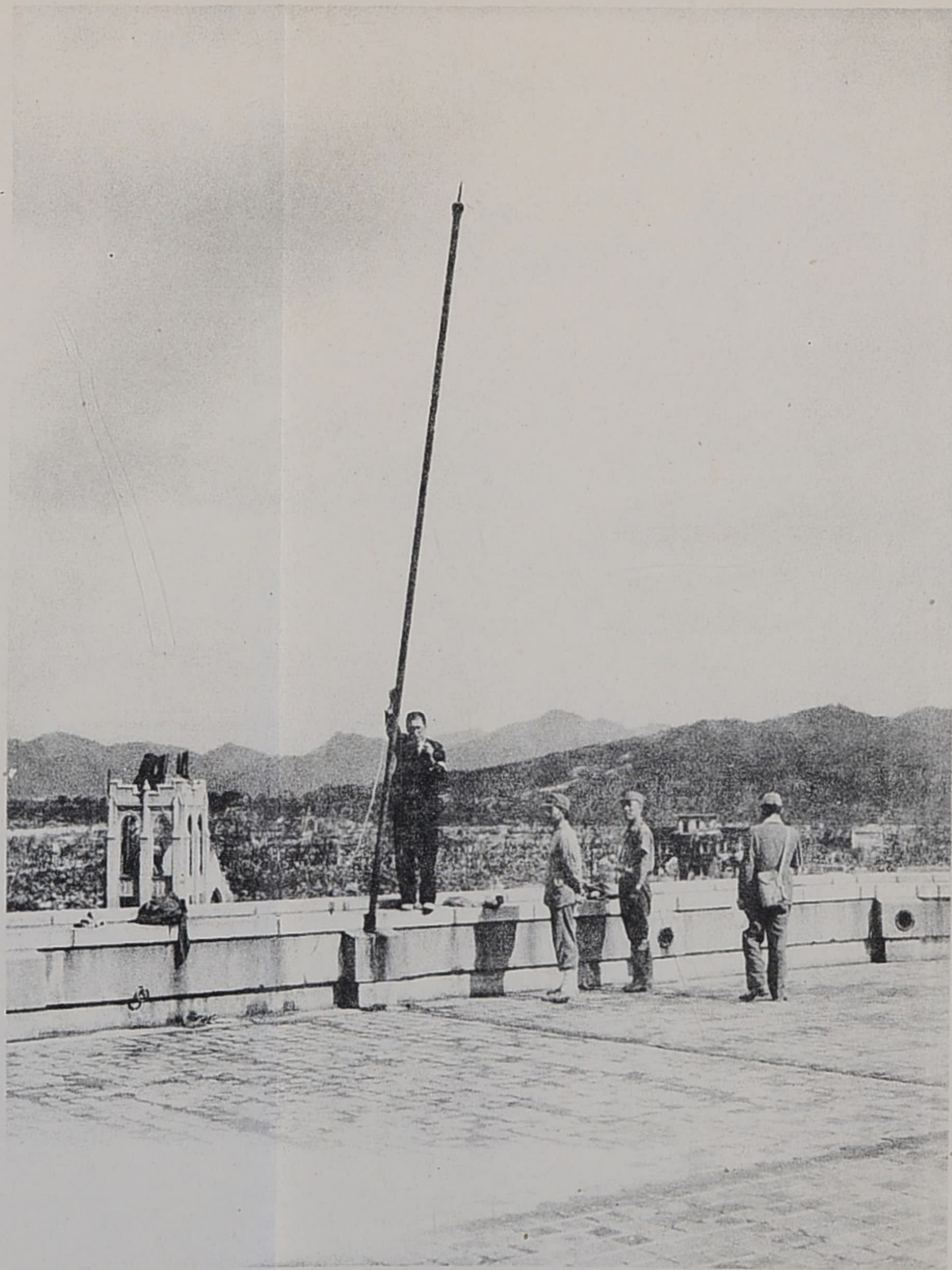
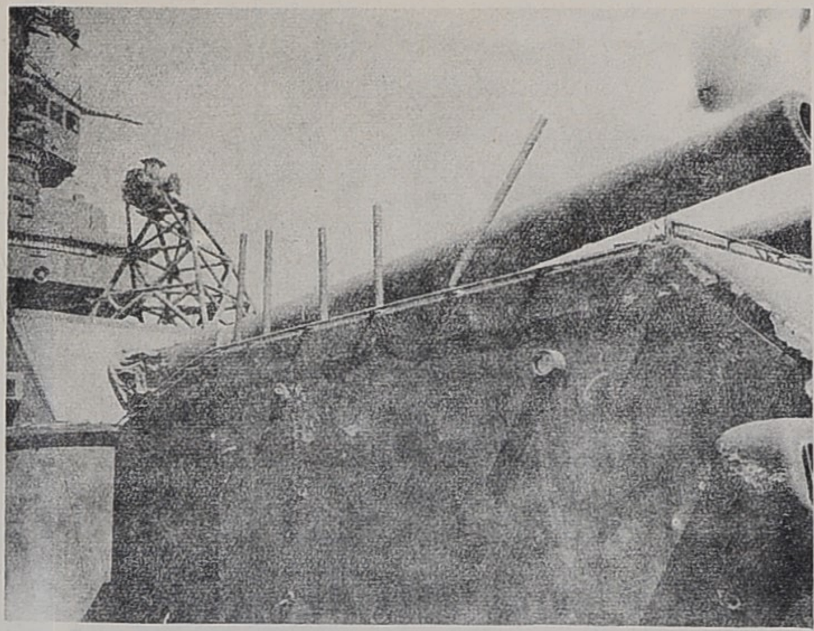


FIGURE 1
N = 17
H = 7
MAXIMUM PRESSURE (p.s.i.)
DISTANCE FROM GROUND ZERO (Feet)
40
30
20
10
0
1000
2000
3000
4000
5000
6000



1. A flagpole and lightning conductor bent by the force of the blast wind in Hiroshima. Distance 3200 ft., peak pressure 9.2 p.s.i.

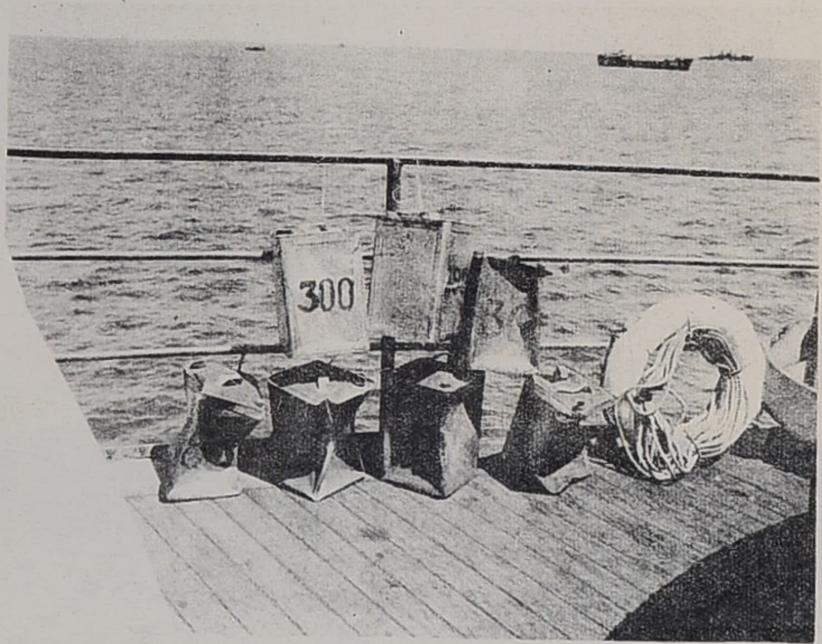


2. A series of blast pipes, of which only the longest has yielded, mounted at Bikini near a foil meter tower.

3. A crushed petrol can in the Mitsubishi works at Nagasaki. Distance 3200 ft., peak pressure 14 p.s.i.

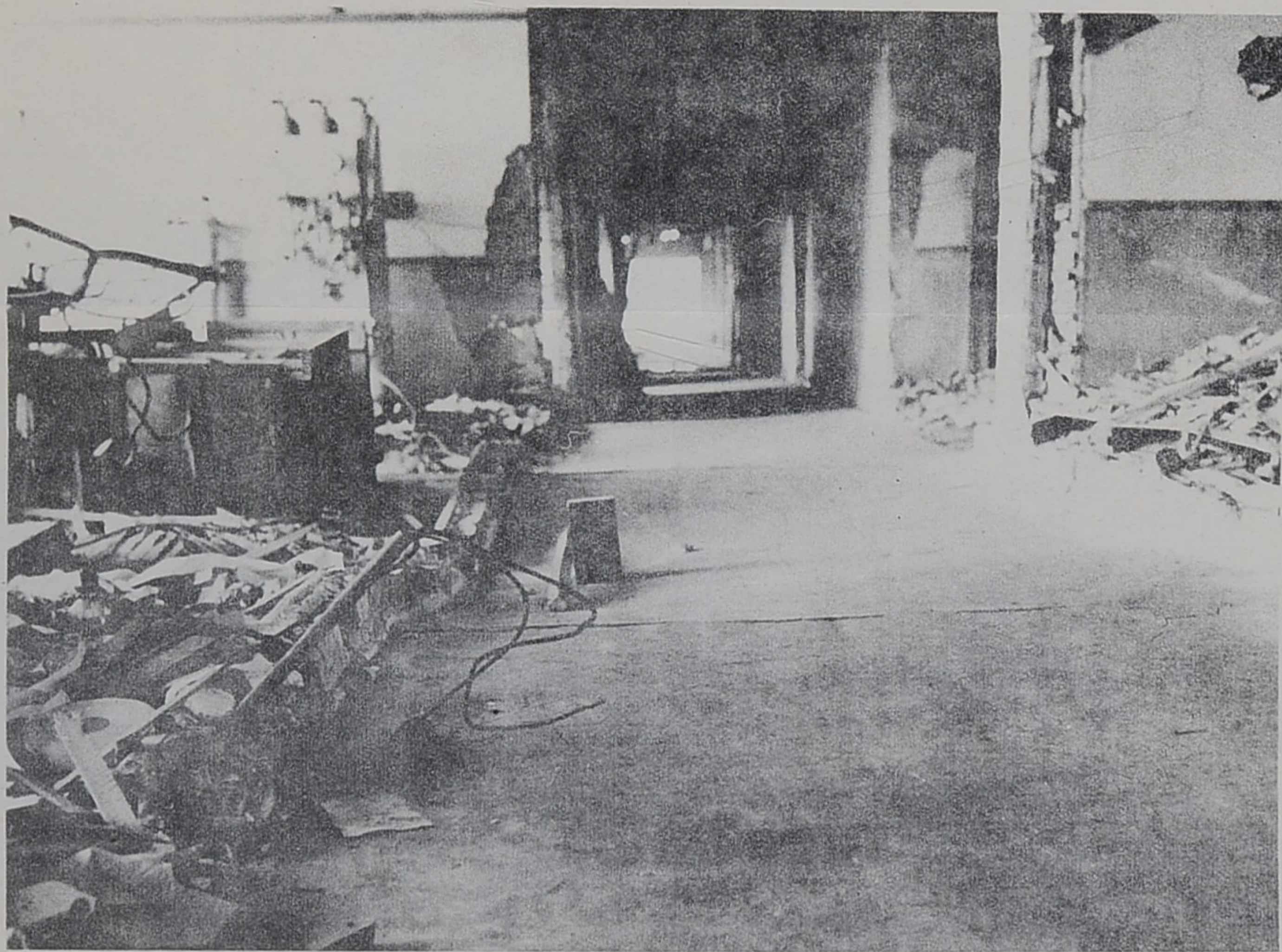
4. A crushed oil can in Hiroshima. Distance 4100 ft., peak pressure 6 p.s.i.

5. A crushed 40 gallon oil drum in Hiroshima. Distance 900 ft., peak pressure 20 - 30 p.s.i.

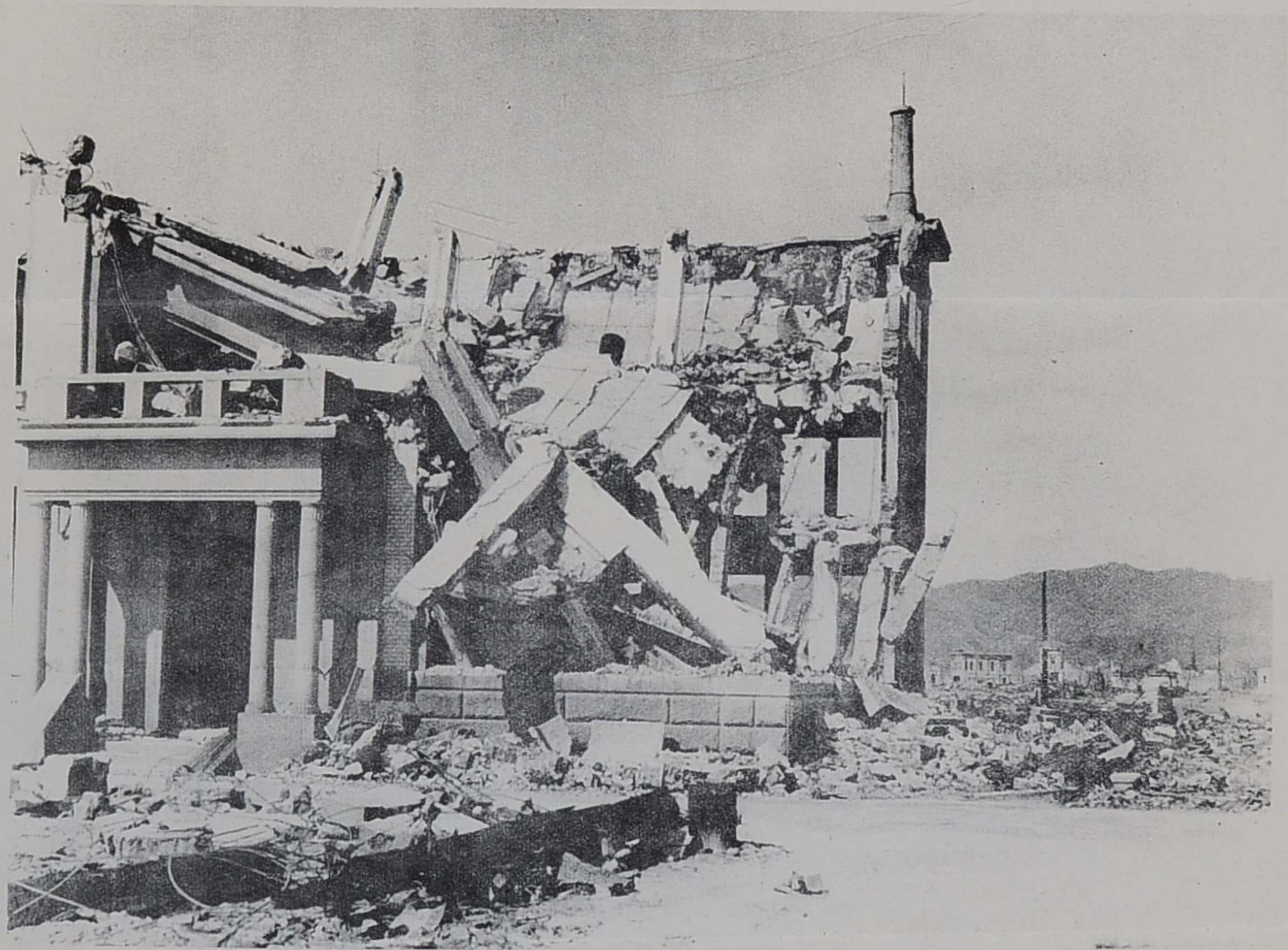


6. Crushed 5 gallon drums at Bikini covering pressure range 3 - 30 p.s.i.

7. Crushed blue-print container from Hiroshima. Distance 5000 ft., peak pressure 3.8 p.s.i.



8.. Dished concrete panels of the ground floor of the Administration Building in the Torpedo Factory at Nagasaki. The basement was practically air tight and was used as an air - raid shelter. Distance 4050 ft., peak pressure 10 p.s.i.



9. A reinforced concrete building almost vertically under the Hiroshima bomb. The building did not have a steel frame. Peak pressure 30p.s.i.